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FRACTURE BEHAVIOR PREDICTION FOR

RAPIDLY LOADED SURFACE CRACKED SPECIMENS

by

ADA 221 125

M. T. Kirk

E. M. Hackett

DTRC/SME-88-45 Fracture Behavior Prediction for Rapidly Loaded
Surface Cracked Specimens



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Mark T. Kirk¹ and Edwin M. Hackett¹

Fracture Behavior Prediction for Rapidly Loaded Surface-Cracked Specimens

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ABSTRACT: The feasibility of predicting the fracture behavior of surface cracks from shallow cracked bend specimens was investigated. The material studied was a high-strength steel stress relief embrittled to various levels of Charpy-V notch impact toughness. Material toughness was quantified in terms of the J-integral at total specimen failure (J_{crit}), using both deeply notched and shallow-notched bend bars (single-edge notch bend) [SE(B)] dynamically loaded in a drop tower impact testing machine. These data were compared with the fracture behavior of rapidly pressure loaded part-through surface cracked bend [PS(B)] specimens, which had a shallow surface flaw introduced at the specimen midspan. For highly embrittled material (Charpy V-notch energy (CVE) between 10 J and 24 J), J_{crit} values measured using shallow crack SE(B) specimens were consistently higher than deep crack J_{crit} values due to the shorter crack size, as well as increased plastic energy dissipation within the specimen. These higher J_{crit} values served as better predictors of the PS(B) fracture performance than did comparable deep crack values. Even though J_{crit} cannot be considered a geometry independent measure of fracture toughness for shallow through cracks, values of this parameter determined using test specimens containing them appear to have considerable engineering utility for predicting the fracture behavior of part-through surface flaws.

KEY WORDS: J-integral, dynamic loading, fracture mechanics, elastic-plastic fracture, short crack, surface crack

The value of the J-integral at or near the onset of ductile crack growth has been recognized for some time to be an appropriate single-parameter measurement of upper-shelf fracture toughness, provided certain criteria are satisfied. These criteria—associated with maintenance of a Hutchinson-Rice-Rosengren (HRR) singularity at the crack tip—are typically satisfied in laboratory experiments by testing deeply cracked (a/W between 0.50 and 0.75) specimens loaded primarily in bending. In this case, the HRR singularity continues to exist past net section yield due to a high-stress triaxiality at the crack tip [1]. Using slip line field analysis, Matsoukas, Cotterell, and Mai [2] have determined that the crack tip stress triaxiality decreases with decreasing crack size. This reduction manifests itself experimentally as an increase in the observed fracture toughness with decreasing initial crack depth [3-5].

You and Knott [6] experimentally demonstrated that, for a given maximum crack depth, fracture initiation toughness measured using bend specimens containing shallow through flaws compares well with that measured at the maximum depth of semielliptical

¹ Mechanical engineer and materials engineer, respectively, David Taylor Research Center, Annapolis, MD 21402.

surface flaws. This observation may be used to advantage during fracture safety analyses of structures containing shallow surface flaws by using the techniques of Sumpter [7]. Sumpter has suggested that toughness levels for surface cracks may be quantified in terms of the J -integral by testing bend specimens with through flaws of similar depth. Sumpter derived J formulas for specimens of this type which compare well with elastic-plastic finite-element results. This approach sacrifices the specimen independent properties of J_{Ic} values determined with deeply cracked specimens in favor of a more accurate engineering approximation to the fracture resistance of surface flaws typically encountered in service.

In this investigation, the feasibility of using this approach for a high-strength steel alloy stress relief embrittled to various levels of Charpy V-notch impact toughness was investigated. Material toughness was quantified in terms of the J -integral at total specimen failure (J_{crit}), using both deeply notched and shallow-notched bendbars dynamically loaded in a drop tower impact testing machine. These data were compared to the fracture behavior of rapidly pressure loaded part-through surface cracked bend specimens, which had a shallow surface flaw introduced at the specimen midspan.

Material Investigated

Typical chemical composition and strength properties for high-strength steel are given in Table 1. The subject of this investigation was the fracture tolerance of this alloy in a stress relief embrittled condition. In high-strength steel, stress relief embrittlement changes the typical high-energy dissipation upper shelf fracture mode (transgranular fracture by microvoid coalescence) to a low-energy dissipation intergranular fracture mode. This change reduces the material fracture resistance, as illustrated by the reduction of the Charpy V-notch energy (CVE) with time held at the embrittling temperature, as shown in Fig. 1. For purpose of correlation of J_{crit} values, the average CVE will be used as a qualitative index of the degree of material embrittlement. This use of CVE is only appropriate when the fracture mode does not vary with specimen size or type, as was the case for this material.

TABLE 1—Typical chemical composition and strength properties^a of high-strength steel.

Element	Weight %
C	0.08
Mn	0.67
Si	0.31
P	0.02
S	0.014
Cr	1.52
Ni	3.1
Mo	0.43
Cu	0.2
V	0.003
Ti	0.001
0.2% Offset yield strength, MPa	574
Ultimate tensile strength, MPa	674
Elongation, %	24
Reduction in area, %	66

^aStrength properties measured using round tensile specimens of 50.8-mm gage length and 12.8-mm diameter.

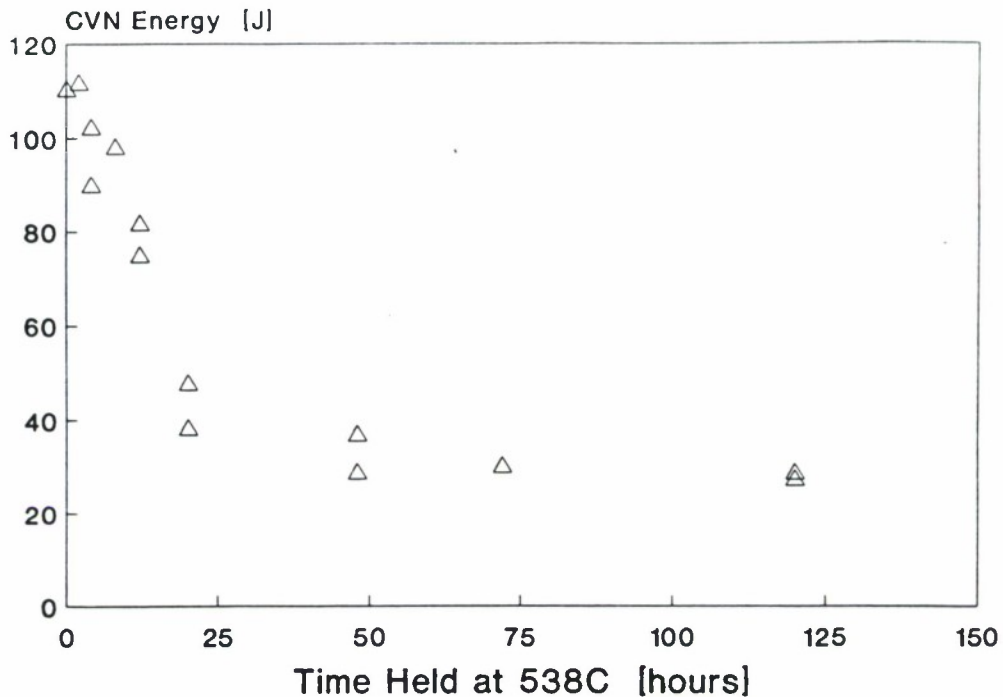


FIG. 1—Stress relief embrittlement of high-strength steel as evidenced by reduction of CVE with time held at the embrittling temperature.

Experimental Approach and J-Integral Formulas

Deep Cracked Single-Edge Notch Bend [SE(B)]

Three-point bend specimens (Fig. 2a) having initial precrack depths between 0.66 and 0.70 a/W and nominal thicknesses of 25.4 mm and 50.8 mm were tested. All specimens were dynamically loaded in a drop tower using the procedures developed by Hackett and Joyce [8]. Load was measured during the test using strain gages attached at the quarter span points of the specimen and wired to form a full bridge. The relation between the bridge output and the applied load was established prior to each test by statically loading the specimen in the elastic regime. Hackett, Joyce, and Shih [9] have determined that loads determined in this manner compare well with those measured with a load cell, even in the post-yield regime. Crack opening displacement was also measured using a capacitance transducer placed in the notch. The J_{crit} value was calculated using the formula due to Rice [10]

$$J_{crit} = 2 \cdot A/B_{net} \cdot b_0 \quad (1)$$

where

- A = area under the load versus load line displacement curve,
- B_{net} = minimum specimen thickness, and
- b_0 = remaining ligament.

Load line displacement was calculated from the measured crack opening displacement (COD) by multiplying by the factor 1.16, determined by Kirk and Hackett [11] to relate these two quantities for wrought high-strength steel specimens having the same initial crack length. It should be noted that the stress-strain properties of this material are quite similar to those of the material considered herein.

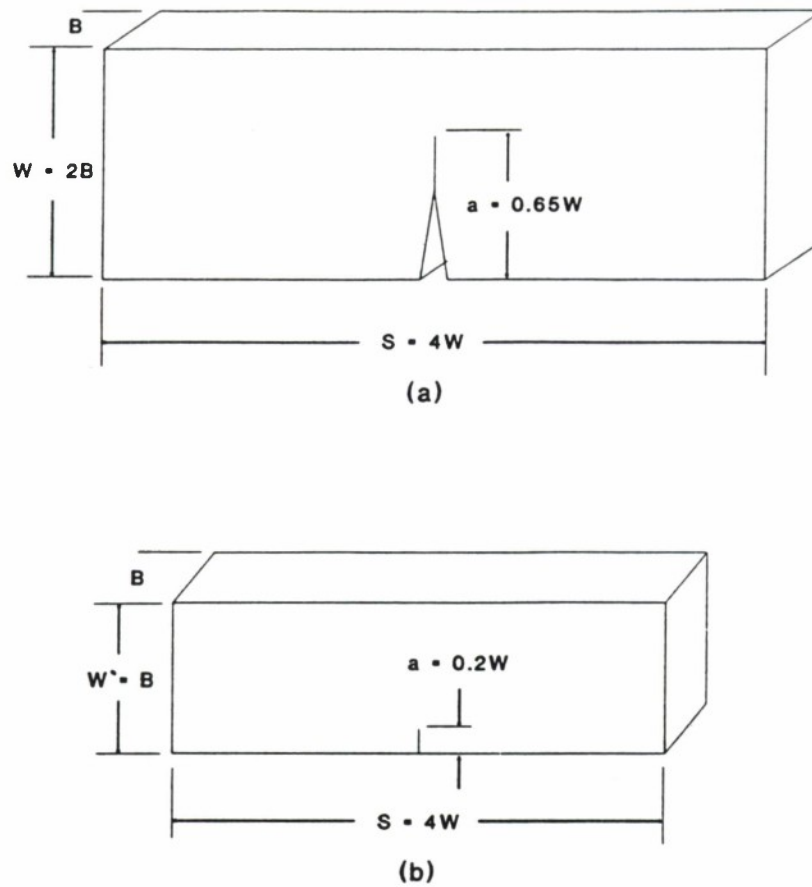


FIG. 2—SE(B) specimens; (a) deep crack; (b) shallow crack.

Shallow Cracked SE(B)

The shallow-cracked three-point bend specimen (Fig. 2b) was designed consistent with the criteria forwarded for the subsidiary bend specimen in British Standard Methods for COD Testing (BS 5762). The specimen thickness (50.8 mm) was the same as the structure whose fracture behavior was to be predicted, while the precrack depth ($a/W = 0.20$ to 0.23) was slightly deeper than the surface crack of interest. In this case, the “structure” referred to is the part-through surface cracked bend specimen described in the next section.

All shallow cracked SE(B)s were tested in a manner similar to that described previously for the deeply cracked specimens. For these specimens, load line displacement was calculated from the displacement measured using a noncontacting eddy-current transducer positioned 50.8 mm from the loading point. As with the load, the relation between the output of these transducers and the actual load line displacement was determined by statically loading each specimen in the elastic region prior to testing. For these specimens, the load line displacement was approximately 1.8 times larger than that recorded by the eddy current transducer.

The formula proposed by Sumpter [7] was used to calculate J_c for specimens of this type. This formula is

$$J_c = \frac{K^2 \cdot (1 - \nu^2)}{E} + \frac{n_p \cdot U_p}{B \cdot b_0} \quad (2)$$

where

K = linear elastic stress-intensity factor calculated from maximum applied load,

ν = Poisson's ratio,

E = Young's modulus,

B = specimen thickness,

b_0 = initial remaining ligament

U_p = plastic component of the area under the load versus load line displacement trace, and

$$n_p = 0.32 + 12.0(a/W) - 49.5(a/W)^2 + 99.8(a/W)^3 \text{ for } a/W < 0.282$$

$$= 2.0 \text{ for } a/W \geq 0.282.$$

Sumpter demonstrated that J values thus calculated lie within 10% of J values computed using a numerical contour integration in a homogeneous specimen having normalized crack lengths ranging from 0.1 to 0.5.

Part-Through Surface Cracked Bend Specimens, PS(B)

Figure 3 shows the part-through surface cracked bend, PS(B), specimen employed in this investigation. A semielliptical surface flaw of approximately 16.5-mm (0.65 in.) surface extent and 6.35-mm (0.25 in.) depth was introduced at the midspan of each specimen by fatigue extension from an electro-discharge machined notch. Subsequent to fatigue cracking, the beams were welded into carrier plates of high-strength steel. Strain gages were placed along the specimen midspan on the cracked side to record the development of strain during the test. Specimens were then bolted into a test die, which left only the test section free to deform. Loading was accomplished by rapidly applying a pressure pulse to the uncracked surface. The maximum J value applied to the specimen was calculated from the maximum recorded strain using Turner's Engineering- J approach [12], which expresses J as a function of applied strain as follows

$$J = (e/e_y)^2 \cdot [1 + 0.5 \cdot (e/e_y)^2] \cdot G \text{ for } e/e_y \leq 1.2 \quad (3a)$$

$$= 2.5 \cdot [(e/e_y) - 0.2] \cdot G \quad \text{for } e/e_y > 1.2 \quad (3b)$$

where

$$G = Y^2 \cdot S_{yd}^2 \cdot (a/E),$$

e = maximum applied strain,

a = maximum crack depth,

E = Young's modulus,

S_{yd} = dynamic yield stress,

$e_y = S_{yd}/E$, and

$Y = K/(S \cdot a^{1/2})$, linear elastic shape factor.

The solution of Newman and Raju [13] for a semielliptical surface crack in a plate subjected to combined tension and bending loads was used to determine the appropriate Y values. When the specimen failed across the remaining ligament, strain data were sometimes lost. In these cases, the maximum applied strain was calculated from the severity of the applied pressure pulse based on data obtained from similar specimens for which all data were recorded.

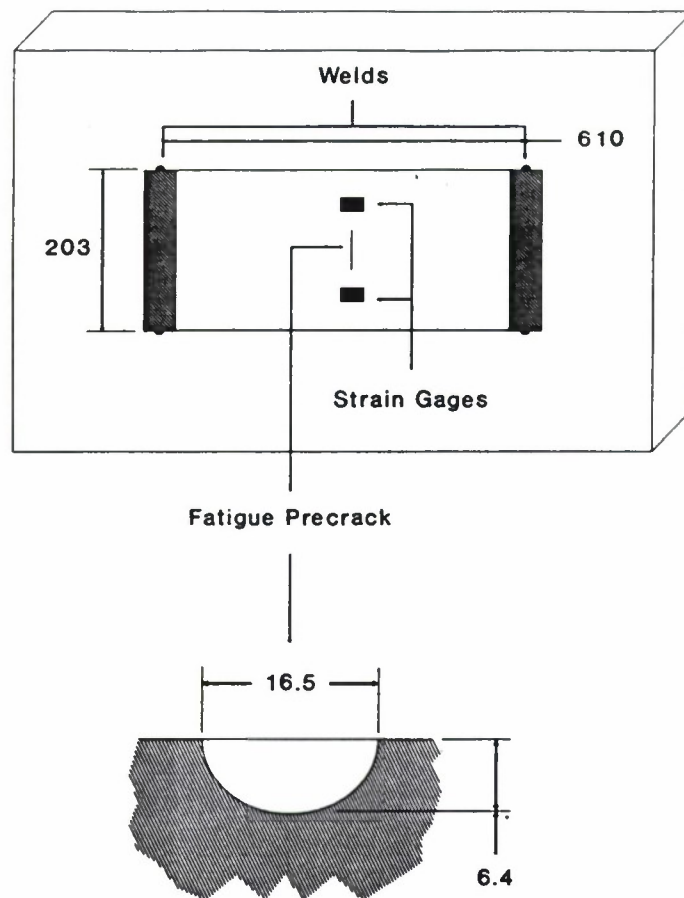


FIG. 3—PS(B) specimen: (a) plan view; (b) detail of precrack at centerline midspan intersection (oriented along midspan). Specimen thickness is 50.8 mm (all dimensions in mm).

Results and Discussion

Figure 4 compares the typical variation of load, or strain, with time for each of the three specimen types tested. These data indicate that all specimens were loaded at approximately the same rate. The small loading rate variations between the different specimens is not expected to influence the properties measured because the material is not very rate sensitive. As indicated in Fig. 5, the 0.2% offset yield strength and ultimate tensile strength only increase by 12% over a four-order of magnitude increase in loading rate. The yield strength value at the highest loading rate (3.5/s)—675 MPa—was employed in the calculation of G in Eq 3.

In Fig. 6, the results of the SE(B) fracture tests are presented. The average CVE values shown were determined by testing CVN specimens cut from the fractured SE(B) specimen halves. Here, average values were used for clarity of presentation; data scatter would have to be accounted for prior to engineering use of these, or similar, data. The ordinate values show the total J absorbed by the specimen prior to section failure (J_{crit}). Due to the intergranular fracture mode exhibited by this material, failure was catastrophic for both fully elastic and elastic-plastic loading records.

The data in Fig. 6 indicate that there is no systematic dependence of J_{crit} on specimen thickness for the deeply cracked SE(B)s. A comparison of the shallow and deep crack SE(B) data indicates that the shallow cracks have considerably more resistance to fracture over the CVE range examined. Moreover, the shallow cracked SE(B)s showed greater sensitivity

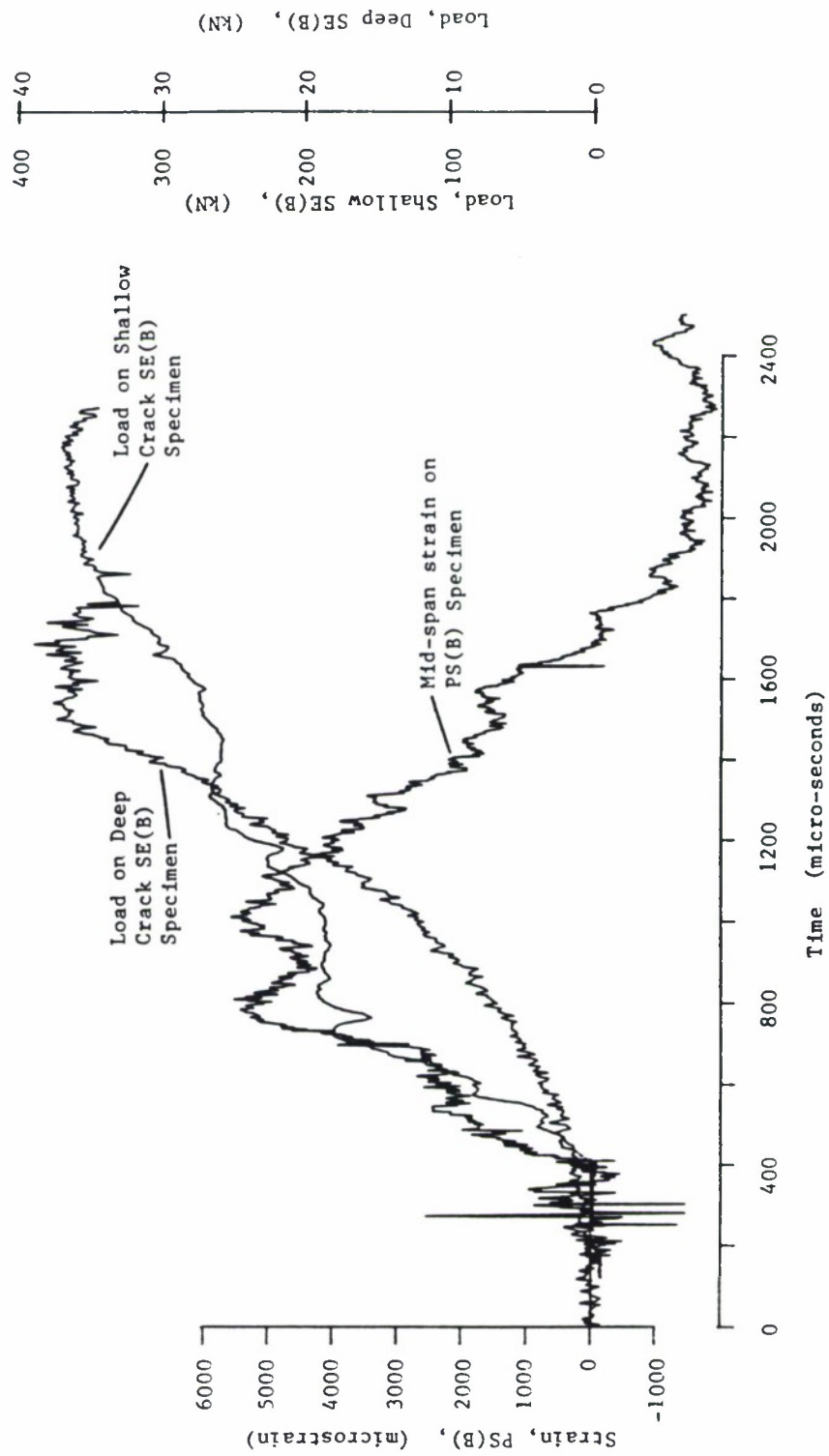


FIG. 4—Typical strain (or time) versus load behavior of deep crack SE(B), shallow crack SE(B), and PS(B) specimens.

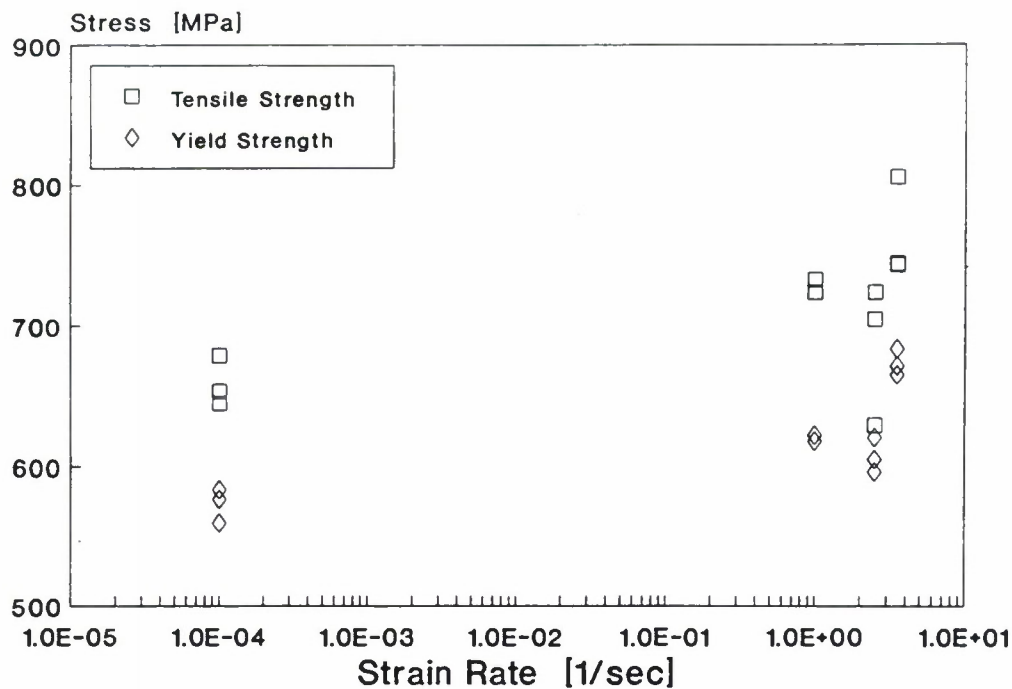


FIG. 5—Variation of 0.2% offset yield strength and ultimate tensile strength with loading rate for embrittled high-strength steel.

to changes in CVE than the more deeply cracked specimens. At an average CVE of 27 J, where the load-displacement behavior was predominantly linear, only a modest increase of J_{crit} was observed with decreasing crack length. However, at higher CVE (54 J), where elastic-plastic load-displacement behavior was observed, considerably greater increases in J_{crit} occurred. It is therefore suspected that elevation of J_{crit} at low CVE is mostly due to a

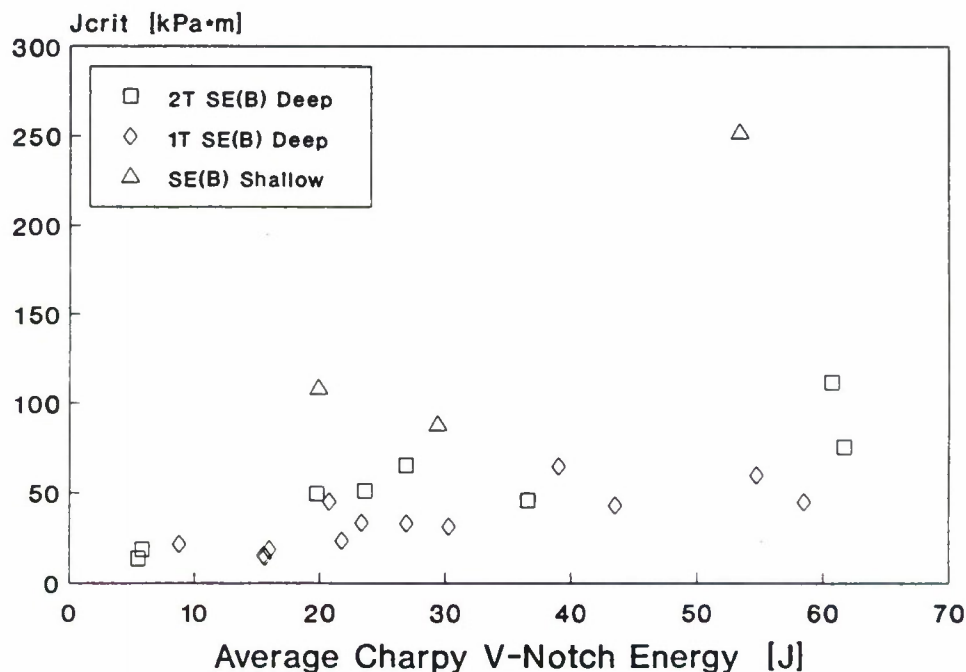


FIG. 6—Variation of the critical J at fracture with the CVE for deep and shallow crack SE(B) specimens of embrittled high-strength steel.

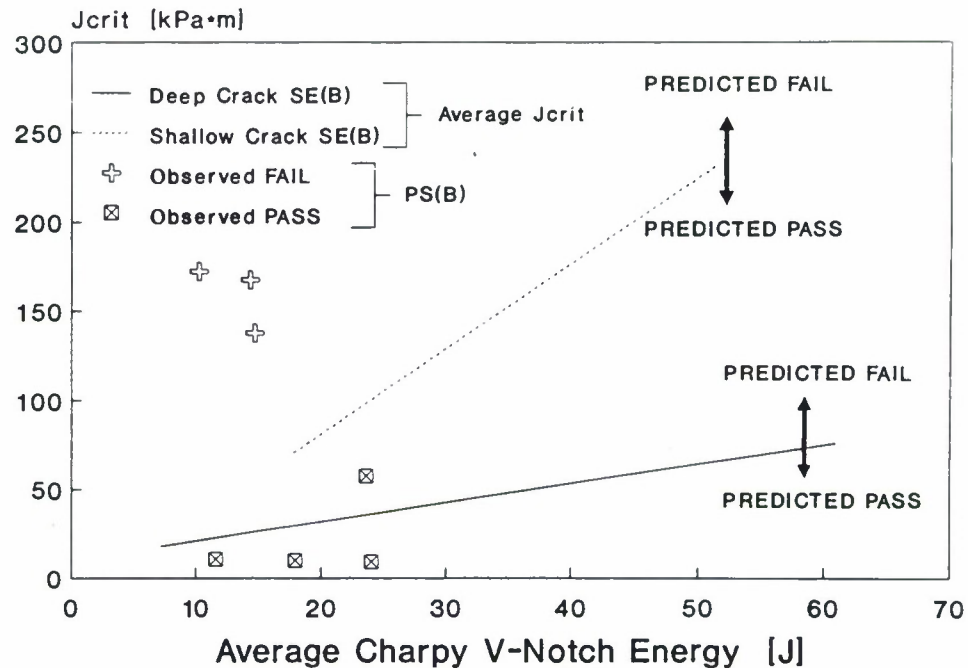


FIG. 7—Comparison of observed PS(B) fracture response to predictions based on data from shallow-crack and deep-crack SE(B) specimens of embrittled high-strength steel.

short crack effect, while the elevation at higher CVE is also attributable to increased plastic energy dissipation.

While the variations of J_{crit} with CVE and initial crack depth shown in Fig. 6 appear reasonable based on physical considerations, the engineering utility of either data set (shallow crack or deep crack) can only be judged by how well the fracture behavior of a surface crack is predicted. To this end, several PS(B) specimens were tested. The results of these experiments are compared to trend lines drawn through the SE(B) data (Fig. 6) in Fig. 7. The shallow crack SE(B) data predicted the results of all PS(B) experiments correctly, while the deep crack SE(B) data predicted one PS(B) specimen, which actually passed, to fail. (A pass is a specimen for which no crack extension was observed, while a fail is a specimen in which crack propagation completely severed the remaining ligament.) Deep crack SE(B) data predicted PS(B) fracture behavior correctly only when mid span strains in the PS(B) specimens remained below yield level. Thus, while the deep crack SE(B) data provide a conservative assessment of the PS(B) fracture behavior, fracture behavior predictions based on shallow crack SE(B) data were seen to be correct for all PS(B) specimens tested. While this approach lacks the geometry independent qualities of a J_{Ic} criteria, there seems to be considerable engineering merit in testing a laboratory specimen designed to model a surface flaw.

Conclusions

For the steel used in this investigation, embrittled to an average Charpy V-notch energy (CVE) between 10 J and 24 J, the following conclusions follow from the data presented herein:

1. Use of the value of the J -integral at complete specimen separation (J_{crit}), measured using deep crack ($a/W = 0.65$) bend specimens, to predict the fracture behavior of part-through surface crack bend [PS(B)] specimens provides conservative results.

2. J_{crit} values measured using shallow crack bend specimens were consistently higher than deep crack values due to the shorter crack size as well as to increased plastic energy dissipation within the specimen. These higher J_{crit} values served as better predictors of the PS(B) fracture performance than did comparable deep crack values.

3. Even though J_{crit} cannot be considered a geometry independent measure of fracture toughness for shallow through cracks, values of this parameter determined using test specimens containing them appear to have considerable engineering utility for predicting the fracture behavior of part-through surface flaws.

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